STUDY OF CRACK DYNAMICS IN ICE BY MEANS OF ELECTROMAGNETIC METHODS

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LONG-TERM GOALS

The long-term goal of this project is understanding the physical mechanisms that make crack velocities in saline and fresh water ice so different. This understanding will improve theoretical predictions of ice forces.

OBJECTIVES

In this project we measured crack velocity as a function of ice microstructure, temperature and a load applied to ice. Experimental techniques based on electromagnetic measurements are used to determine crack velocities in various types of ice. Special attention was given to the dynamic interaction between cracks growing in ice and such micro structural ice features as brine pockets, brine channels and grain boundaries. Such interactions plus the high ductility of sea ice are suspected to be responsible for the very low velocity of cracks in sea ice. Results were analyzed according to recent advances in the general theory of crack dynamics and crack interaction. It is expected that this work will answer the question of why sea ice cracks have such low velocity and contribute to the understanding of the dynamics of ice fragmentation.

APPROACH

Experimental techniques based on measurements of electromagnetic emissions (EME's) from cracks and changes in ice electrical conductance and capacitance were used to determine crack velocities in various types of natural and artificial ice. The techniques are characterized by high-time resolution (< 1ms) and the capability to detect micro cracks (1 mm^2).

SCIENTIFIC/ TECHNICAL RESULTS

Freshwater and Saline Ice

We have measured crack velocities in a wide variety of ice types: columnar sea ice, columnar lake ice, and laboratory-grown saline and freshwater columnar and granular ice. Mode I and II cracks were studied in a temperature range from –5°C to –35°C. The sample dimensions ranged from 0.05 to 30 meters. The experiments were conducted in the Ice Research Laboratory at Thayer School of Engineering, at Barrow, Alaska, and on Lake Mascoma, New Hampshire. The main findings of this experimental research can be summarized as follows, (Petrenko and Gluschenkov 1996).

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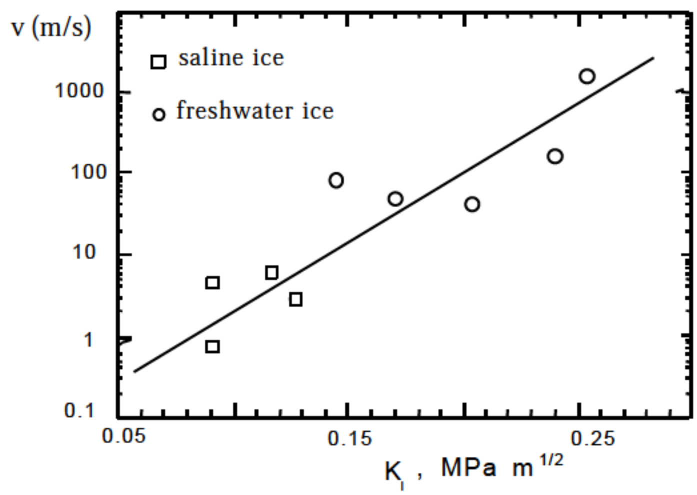

Figure 1. Average velocity of cracks, v, versus fracture toughness, K_1, in the laboratory-grown columnar ice at T = –11°C.

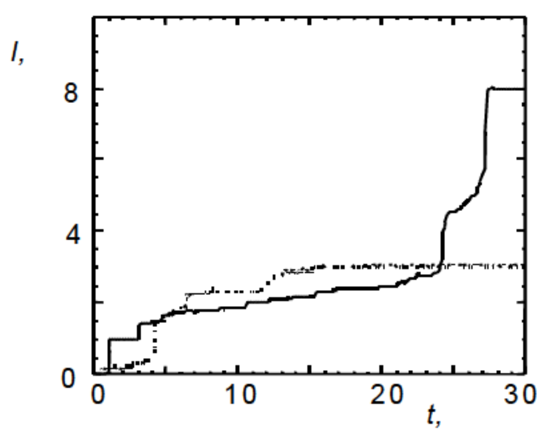

Figure 2. Crack length-versus-time records of two laboratory grown specimens of saline columnar ice. T = –11°C.

1. A drastic difference between the average crack velocities in saline and freshwater ice was found. While in saline ice the average velocity was 0.85 to 18 m/s, in freshwater ice it was in the range of 100 to 1320 m/s, see Figure 1.
2. This difference in crack velocities disappears at temperatures below –35°C, when the liquid inclusions are frozen (Table 1) and Figure 3.
3. The maximum crack velocities, which correspond to the propagation of cracks between obstacles, were found to be comparable in both types of ice.
4. In *saline* ice, cracks advance discontinuously (fast jumps and stops), see Figure 2. The typical distance between obstacles in saline ice ranges from 3 to 10 mm in laboratory-grown ice and from 4 to 36 cm in first-year sea ice. These distances were found to be on the scale of the typical spacing between drainage channels and grain boundaries in sea ice.
5. The most convincing evidence of the increased resistance to crack propagation due to unfrozen water came from a remarkable correlation found between the temperature dependencies of v_C and the water content in sea ice, see Figure 3.

Ice with Artificial Liquid Inclusions

To examine the idea that the remarkable difference in crack speeds in freshwater and saline ice is attributed to the dynamic resistance of unfrozen water inclusions, we performed a series of crack velocity measurements on ice samples having artificial channels filled with different liquids, Petrenko and Li 1996. Thin cylindrical holes 8 mm in diameter were oriented perpendicularly to the crack tip. In these tests, the pores were either empty or filled with one of the following unfrozen liquids: salt water, fluorocarbon, 1-octanol and mercury. The following observations can be made:

1. "Empty" (dry) holes don't resist crack propagation and sometimes even accelerate cracks.
2. Liquid inclusions in ice behave as major obstacles for dynamically growing cracks, decreasing the crack velocity by orders of magnitude, see Figures 4 and 5. In ice samples with empty holes it typically took just 50 ms for a crack to split the sample but 50 ms (10^3 times as much) when the hole was filled with 1-octanol. As it is seen in Figures 4&5 the cracks had the lowest velocity when crossing the holes, but the liquids retarded cracks even at some distance.
3. Basing on these preliminary tests, we suggest that parameters which define the ability of a liquid to resist crack propagation are, most likely, its viscosity and mass density. More tests with various liquids are needed to confirm this hypothesis.
4. Crack velocity, though indicating the strong interaction between cracks and liquid pores, may not be the best quantitative parameter when details of the interaction (for example dependence on the distance between the crack and the pore) are important. The reason is that the force applied to the sample, the elastic and kinetic energies of the sample change during crack propagation. A better parameter to study is a dynamic fracture toughness, K_{ID}.
5. A theoretical model and further experiments are necessary to understand the physical mechanisms of the retardation of cracks in media containing liquid inclusions.

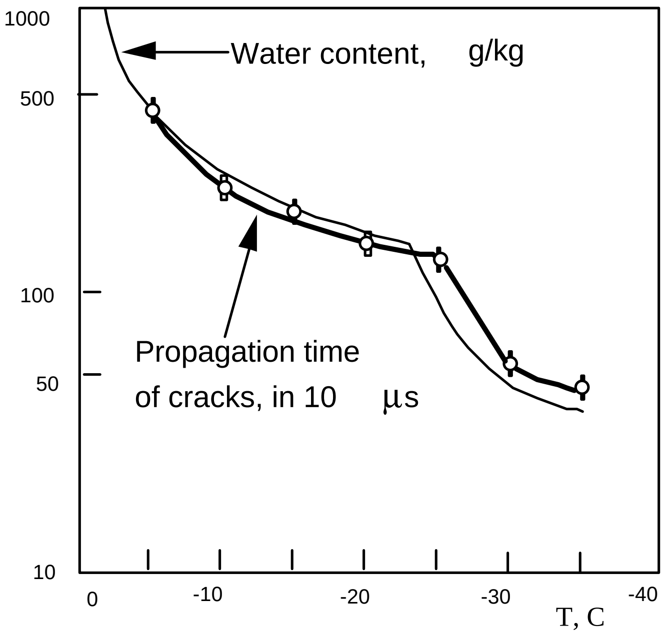

Figure 3. The correlation between water content in "standard" saline ice (after Weeks and Assur, 1967) and the crack propagation time (inverse velocity)measured in saline columnar ice.

TABLE 1. Crack Mean Velocities In First–Year Sea Ice*

Sample Type and Size, m	Ice Surface Temperature, °C	Crack Orientation	Loading Time, s	Measurement Method	Average Crack Velocity v_C, m/s
floating, wet 1.5×1.5×1.4	–19.7	| | to (0001)	250	resistance	8.2
floating, wet 3.0×3.0×1.4	–22.3	| | to (0001)	830	resistance	12
floating, wet 3.0×1.4×1.4	–22.3	⊥ to (0001)	540	resistance	8.9
floating, wet 3.0×3.0×1.4	–20.6	| | to (0001)	7	resistance	18
floating, wet 2.0×2.0×1.4	–25.3	| | to (0001)	1200	resistance	16.1
floating, wet 2.0×1.1×1.4	–25.3	⊥ to (0001)	1300	resistance	15.6
floating, wet 30×30×1.4	–31.2	| | to (0001)	250	resistance	7.5
floating, wet 0.5×0.5×1.4	–31.2	| | to (0001)	300	resistance	3.4
floating, wet 2.4×2.4×0.3	–7.4	| | to (0001)	N/A	resistance	9.3
floating, wet 2.4×2.4×0.3	–7.4	| | to (0001)	N/A	resistance	9.2
dry 0.7×0.4×0.1	–35 (uniform)	⊥ to (0001)	1	EME	220
dry 1.0×0.6×0.1	–35 (uniform)	⊥ to (0001)	1	EME	290

EME = electromagnetic emission; N/A = not available.

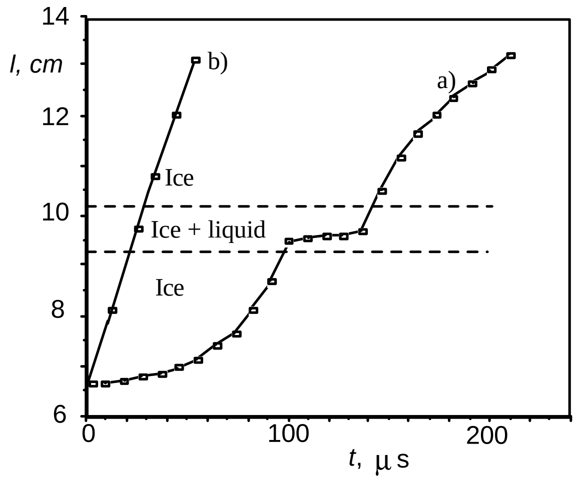

Figure 4. a) Crack length vs time in a sample of freshwater ice with a hole filled with liquid fluorocarbon. T = -10 C. b) Same with an empty hole.

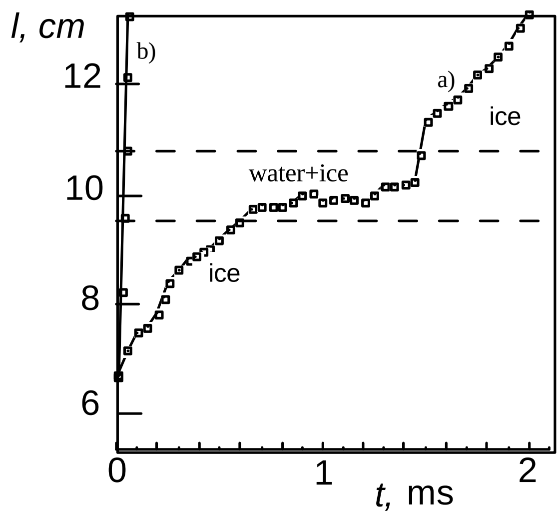

Figure 5. Crack length vs time in a sample of freshwater ice with a hole filled with salt water. T = -10 C. b) Same with an empty hole.

IMPACT FOR SCIENCE

This study provided for the first time systematic field and laboratory data on crack velocity in freshwater ice, saline ice, and ice with artificial voids filled with different liquids. The dramatic differnce between crack velocity in freshwater ice and saline ice was found. The laboratory experiments indicated without any ambiguity that unfrozen water is responsible for that difference. The findings of this project already contributed to our understanding of the physical mechanisms of dynamic fracture of ice, and will be used to construct a quantitative theory that will predicts crack velocity in ice as a function of the ice structure and experimental conditions.The results may also be used in future to predict dynamic forces exurted by ice on engineering structures.

TRANSITIONS

None

RELATED PROJECTS

None

PUBLICATIONS:

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